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INVESTIGATION OF THE STRESS-STRAIN STATE OF COMPOSITE MATERIALS WITH A GRID REINFORCEMENT

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16. Abstract The authors of this article draw the following conclusions from their work:
1. In composites reinforced with grids, the stress-strain of the matrix within the limits of each cell is uniform.
2. Grids which are oriented in directions other than the axis of tension change the stress direction. Rotation of stresses in fiber and matrix occur then on opposite sides.
3. Load-carrying capacity of grid fibers depends on orientation and the modulus of elasticity. Maximum load-carrying capacity has fibers oriented at 0° to tension axis-- minimum-- 45°.

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INVESTIGATION OF THE STRESS-STRAIN STATE OF COMPOSITE MATERIALS WITH GRID REINFORCEMENT

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A significant disadvantage of composite materials (composites), reinforced with unidirectional fibers, is a sharply expressed anistropy of physical properties. A whole series of studies [1-4] confirm that reinforcement with grids makes the properties of composites more uniform. /35*

Nevertheless, in composites reinforced with grids, there is a noticeable effect from the orientation of fibers of the grids relative to the direction of external load on the properties. In references [2-4], it is shown that the orientation of grid fibers affects strength, and also the mechanisms of deformation and rupture of composites. Therefore, a study of distribution of stresses between the components of a composite (grid fibers and matrices) must give us additional information on the mechanics of these phenomena.

In the work for studying the stress-strain state, when stretching models of the composites reinforced with grids, a polarization-optical method was used. The flat models of composites were made from optically sensitive material on a base of ED-5 epoxy resin, with cold hardening, first of the cast fiber, and then the poured frame of the fibrous material of the matrix. A varying content of plasticizer and change in properties of the material in time, permitted obtaining a relationship of the modulus of elasticity of the fiber and matrix in a range from 8.0 to 2.0, which corresponds to the relationship of the modulus of elasticity of most actual metallic composite materials. The

* Numbers in the margin indicate pagination in the foreign text.

models were studied with orientation of the fibers to the tension axis 0° (90°), 15° (75°), 30° (60°), and 45°. The nominal dimension of a side of a cell was assumed to be 24 mm, with width of the fiber 2.3 mm, thickness 1.9 mm and total thickness of the model 4.0 mm. The peculiarities of manufacturing the models (the fiber twice as thin as the total thickness of the model) permitted obtaining complete quantitative information on the stress-strain state of the matrix, whereas, the possibility of precise quantitative determination of stresses in the fibers by determining the order of interferences was difficult due to the effect of averaging the stresses.

Observation of an optical picture of interferences when stretching sample models shows that qualitatively, the stress-strain state within the cell can be considered uniform at all angles of orientation of the fibers and other loads, although, on sections of the matrix adjoining the boundary of the section with a lateral fiber (orientation 90°), there do occur, zones, insignificant in size, of decreased difference of the main stresses, which is explained by retarding of deformation of the /36
matrix due to smaller deformation of the lateral fiber. This effect of fibers oriented at large angles to the tension axis is most strongly apparent when their orientation is 90°, and noticeable at 75 and 60°, decreasing with a decrease in the angle (Figure 1). Inasmuch as the effect of fibers noted is observed only in the thin layer of the matrix near the boundary and the deviation of the stress-strain state in this layer does not exceed 0.1-0.2 of the order of interferences, one can assume that the introduction of grids does not affect uniformity of the stress-strain state of the matrix during stretching. This conclusion is supported by observation of a picture of isoclinic lines in a matrix: at all angles of fiber orientation, the field of the matrix within the cells is a dark field of isoclinic lines of a single angle, that is, the direction of effect of the main stresses is the same within each cell and does not change

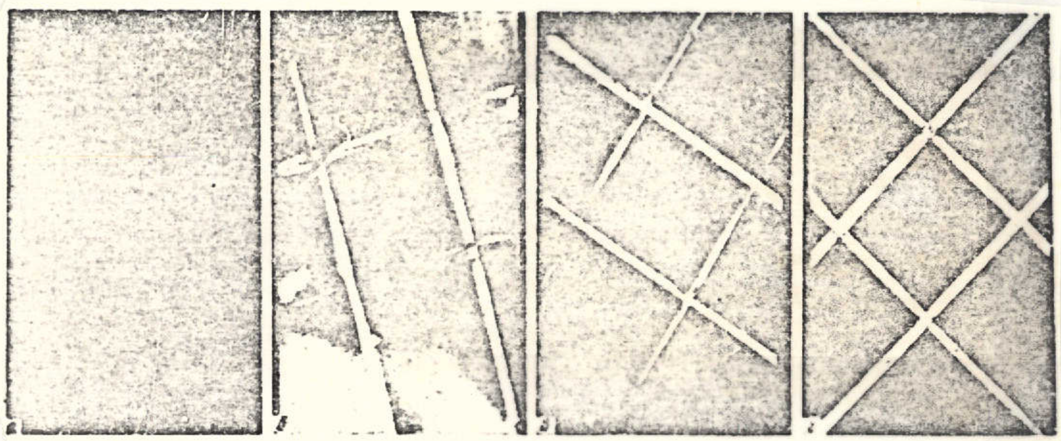

Figure 1. A picture of interferences depending on the orientation of fibers in relation to the tension axis.
Angle of orientation: a-- 0° (90°); b-- 15° (75°); c-- 30° (60°); d-- 45°.

from cell to cell. This mechanism is true for fibers.

It was observed here that a zero isoclinic line in each of the components does not coincide with the direction of tension for cases of orientation of fibers with grids differing from 0° (90°), and here the rotation of the main stresses in the fibers and matrix occur on opposite sides. In other words, the direction of main stresses in the components does not coincide with the direction of tension, and the angle of rotation depends on the orientation of the fibers (Figure 2) and the relationship of the modulus of elasticity of the components. For fibers, these dependencies reflect only a general mechanism of the effect of factors mentioned on the angle of rotation of stress, inasmuch as the effect of summation of stresses affects the quantitative factors.

In this work we also studied the effect of orientation on the contribution of grid fibers to strength of the composite.

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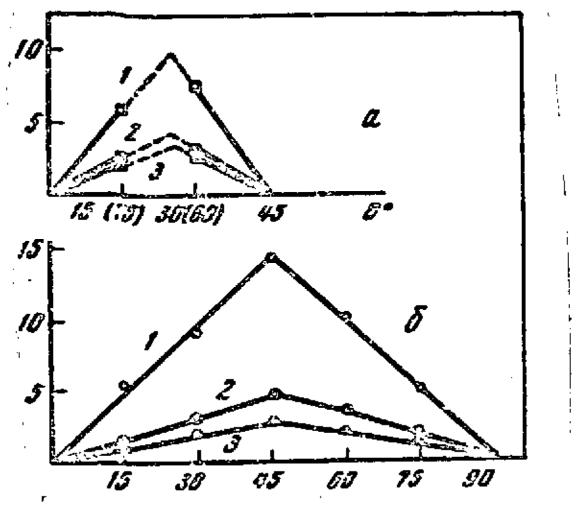

Angle of orientation, degrees

Figure 2. Dependence of the angle of rotation of main stresses in components on the orientation of grid fibers.
a-- matrix; b-- fiber;
1-- E_f/E_m=5.10; 2-- E_f/E_m=3.50;
3-- E_f/E_m=3.14.

It was observed that a uniform order of interferences in fibers oriented at different angles to the tension axis, reached different sizes of general load on the composite. For attaining uniform stress-strain state in fibers, the larger the load on a composite, the larger the angle of orientation of the fibers must be in a range of orientation 0-45°; and in a range of orientation 45-90°, one observes the inverse relationship. The load-carrying capacity of fibers, conditionally accepted, oriented at an angle of 0°, per unit, can be compared to the load-carrying capacity of other fibers with this condition, inasmuch as their relationship is inversely proportional to the relationship of corresponding total loads on the composite:

$$\frac{H_\theta}{H_0} = \frac{P_{f\theta}}{P_{c\theta}} \cdot \frac{P_{c0}}{P_{f0}} = \frac{P_{c0}}{P_{c\theta}} \quad \text{when} \quad P_{f\theta} = P_{f0}, \qquad (1)$$

where $H_o P_{fo}$ and P_{co}-- are the load-carrying capacity, the load on the fiber, and the total load on the composite, respectively, with orientation of the fiber 0°; H_θ, $P_{f\theta}$ and $P_{c\theta}$-- are the same, with orientation of the fiber θ°.

Thus, knowing the load-carrying capacity of the fiber with /37
orientation 0°, one can determine the load-carrying capacity of a fiber oriented at any degree.

The load-carrying capacity of the fiber oriented at an angle of 0°, is determined, assuming that in the central part of the cell, only the longitudinal fibers affect the stress-strain state, and therefore, a calculation of the load-carrying capacity of the fiber for this section can be found in the same way as for a composite with continuous fiber. Then, if the optical characteristics of the components and the areas of their cross sections are known, it is easy to determine the perceptible component of load: $P_c = 2\tau_{oc} \cdot n_c \cdot F_c$, (2) /38

where P_c-- is the load on the component; τ_{oc}-- the value of the bands of interferences; n_c-- the order of interferences in the component; F_c-- the area of the cross section of the component.

In the process of the experiment, the order of interferences of the matrix were precisely determined, and the order of interferences of the fiber-- only qualitatively, as "equal," inasmuch as the quantitative determination of the order of interferences of the fiber was difficult, due to the effect of averaging the stresses involved with the peculiarities of shape of the models. Therefore, according to formula (2) the load received by the matrices is calculated and the load on the fiber is determined as the difference between the total load on the composite determined directly in the process of the experiment, and the load on the matrix. Then, the load-carrying capacity of the fiber with an orientation of 0° is defined as the relationship of the load received by the fiber to the total load on the composite. On the basis of formula (1), then the load-carrying capacity of the fibers oriented at other angles is calculated. The results of these calculations are presented in Figure 3. As we see, for all relationships of the modulus of elasticity, the law of change of the load-carrying capacity is the same: with an increase in angle of orientation, the load-carrying capacity of the fiber decreases, reaching a minimum at 45°, and in a range of angles 45-90° increases again. Then, hysteresis of load-carrying capacity exists for mutually perpendicular

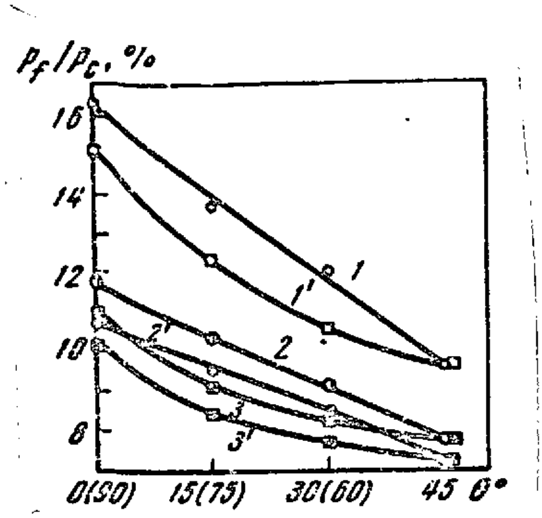

Figure 3. Dependence of load-carrying capacity of the fiber on the angle of its orientation. 1.1'-- E_f/E_m=5.1; 2.2'-- E_f/E_m=3.5; 3.3'-- E_f/E_m=3.14; 1-3-- θ=0-45°; 1'-3'-- θ=45°-90°.

fibers of the grid: the load-carrying capacity of fibers oriented at angles /39 less than 45°, is always higher than in fibers perpendicular to it. A different load of fibers oriented at angles 0-90° is clearly apparent in photographs of the optical picture of interferences presented in Figure 4. As we see, only fibers with an orientation of 45° have the same load.

Figure 4. A picture of interferences depending on orientation of fibers with different total load on the composite
Angle of orientation: a-- 0° (90°); b-- 15° (75°); c-- 30° (60°); d-- 45°.

In a study of the range of the relationships of the modulus (5.10-3.14) the dependence of the load-carrying capacity of the fiber on the relationship of the modulus of elasticity of the components is close to linear. Then, the best coincidence with the theoretical curve constructed for a composite with a close quantitative content of continuous fibers, is observed in fibers with orientation 0°, which supports the correctness of the hypothesis assumed when calculating the load-carrying capacity of longitudinal fibers.

Conclusions

1. It was established that in composites reinforced with grids, the stress-strain state of the matrix during tension within the limits of each cell can be considered uniform.

2. The introduction of grids, whose fibers have an orientation which does not coincide with the axis of tension changes the direction of effect of the main stresses in the components in relation to the axis of tension; then, the rotation of the main stresses in the fibers and the matrix occur on opposite sides. The size of the angle of rotation of the main stresses depends on the orientation of fibers in the grid in relation to the modulus of elasticity of the components.

3. The load-carrying capacity of fibers of a grid depend on their orientation and the relationship of the modulus of elasticity of the components. Maximum load-carrying capacity is observed in fibers oriented at an angle of 0° to the axis of tension, the minimum-- at an angle of 45°.

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